THE IMPORTANCE OF JUPITERS IN A MICROLENSING SEARCH FOR PLANETS. S.J. Peale, *Physics, University of California at Santa Barbara 93106.*

The recently discovered planetary mass bodies around several nearby stars have revealed systems very much unlike our own with the possible exception of Lalande 21185, which seems to have a planet of 1.4 ± 0.2 Jupiter masses (m_J) at 7.5 ± 0.5 AU with period of 32 ± 4 years in a low eccentricity orbit (Gatewood, private communication 1997). The planets around 51 Peg, 55 Cnc, τ Boo, and υ And (Mayor and Queloz, 1995; Marcy, *et al*, 1997; Butler *et al*, 1997) all have masses comparable to m_J and orbital periods of a few days (*i.e.*, located inside 0.2 AU from their stars). The star 47 UMa has a planet of minimum mass 2.4 m_J in nearly circular orbit at 2.1 AU (Butler and Marcy, 1996), 70 Vir has a companion more massive than 6.6 m_J with semimajor axis $a \sim 0.43$ AU and eccentricity $e \sim 0.4$ (Marcy and Butler, 1996), and 16 Cyg B has a planet with a mass greater than 1.5 m_J, $e \sim 0.63$ and $a \sim 3.2$ AU (Cochran, *et al*, 1997). Although there are severe observational selection effects constraining the properties of these detected planetary mass bodies, it is striking that almost 3% of the stars monitored in radial velocity surveys are found to have giant planets at distances much closer to their stars than where they could have formed by accretion of solid planetesimals and subsequent capture of large gaseous envelopes (Butler *et al*, 1997).

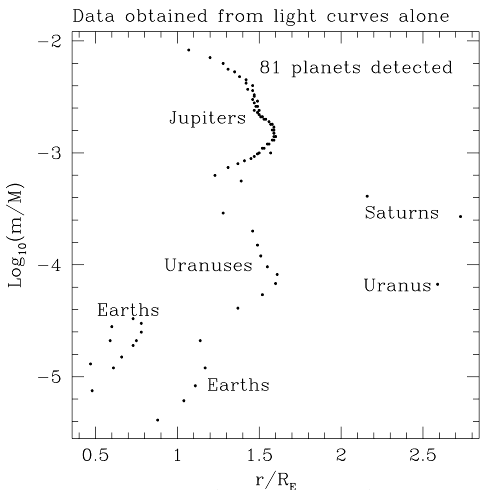
There are several theoretical arguments showing how Jupiters could be removed from their region of formation, and, in some cases, account for the close giant planets. These include torques from spiral density waves in a persistent nebula generated by fully formed planets (Lin, *et al*, 1996), by mutual scattering of planets formed too close together for stability (Rasio and Ford, 1996; Weidenschilling and Marzari, 1996) or by rapid migration of the solid body accretional cores before acquisition of the gaseous envelopes (Ward and Hourigan, 1989; Ward, 1996). If such migration of giant planets or their cores into the region where terrestrial planets might have formed is the rule in planetary system histories rather than the exception, the occurrence of habitable terrestrial planets may be much more rare than we had hoped.

Giant planets that have not migrated far from their place of origin can be detected by radial velocity or astrometric techniques, but only on observational time scales approaching the decades long orbital periods. Current radial velocity and astrometric programs have about a decade long history, and it may be significant that no planet has yet been detected in a Jupiter-like orbit. The fraction of stars having planetary systems with Jupiters orbiting near what would have been the ice condensation point in the respective primordial nebulae might be inferred to be the same fraction of stars that have terrestrial planets persisting in the habitable zones inside the giant planet orbits. Planning the NASA program to attempt the characterization of terrestrial mass planets around stars within 10 parsecs (Beichman, 1996) requires some indication of the frequency of occurrence of such planets on a relative short time scale. The phenomenon of gravitational microlensing offers a means of gaining such statistics---by inference from the detection of Jupiters or by direct detection of the terrestrial planets themselves.

Mao and Paczynski (1991) pointed out that a planet could be detected as a companion of a star by perturbing the light amplification curve of a more distant star (source) that is being gravitationally lensed (microlensing) by the nearer star (lens). Later Gould and Loeb (1992) derived a probability of nearly 20% for detecting a Jupiter about a solar mass star given that a microlensing event was taking place by assuming that a 5% perturbation of the light curve was detectable. The MACHO (MAssive Compact Halo Objects) collaboration has been remarkably successful in detecting approximately 100 microlensing events toward the galactic center (GC) over a two year period (C. Stubbs, 1996, private communication, Alcock *et al* 1996). The possibility of detecting at least 350 events per year with modest upgrades in technology together with a larger dedicated telescope at a good site (C. Stubbs, 1996, private communication) promises a means to gather planetary statistics at a reasonably rapid rate.

The proposed search consists of following ongoing stellar microlensing events involving sources in the center of the galaxy lensed by intervening stars with high time resolution, 1% photometry in an attempt to catch any short time scale planetary perturbations. A two meter telescope in the southern hemisphere would detect the events and three or four additional two meter telescopes distributed in longitude would follow all ongoing events with the above high time resolution photometry (Tytler, 1995). We assume a particular style of planetary system about an assumed number of lensing stars and ask how many of the planets having particular masses and separations can be detected by such a search. A detection probability from Gould and Loeb (1992), given as a function of semimajor axis, is scaled by the planet/star mass ratio m/M and mean lens distance and averaged over the mass function (Peale, 1997).

We assume that a total of 3000 events would be followed over an 8 year period, where the half of the lenses that are members of multistar systems have no planets. (However, note that several of the stars about which planets have been found are members of multistar systems, albeit widely separated.) The remaining 1500 systems all have a solar-system-like distribution but with only 4 or 5 planets. All have a Venus at 0.7 AU and an Earth at 1.0 AU. Half of these lenses have a Jupiter at 5 AU and a Saturn at 10 AU. The remaining 750 lenses have Uranuses in place of the Jupiters and Saturns at 5 and 10 AU respectively and an extra Earth at 2.5 AU. The mass function of the lenses is assumed to be the same as that of the local stars, which is heavily weighted toward spectral class M stars. Three models are treated in Peale (1997), where the masses and separations of the planets are different functions of the lens masses. We consider here only model 3 which fixes both the masses and separations of the planets as listed above regardless of the lens mass. Observational constraints limit



Points are for Model 3 (m_i, a_i invariant), and they are determined from the probability distributions of lens masses and of projected lens−planet separations.

the number of detectable Earths and Venuses that are actually detected, but nearly all of the Jupiters and Saturns that are detectable according to the probabilities are, in fact, detected because of the day long time scale of the latter perturbations (Peale, 1997).

We assume that m/M and r/R_E, obtainable from the light curve alone, are the only parameters available from the microlensing search data. (r is the projected planet-star separation and R_E is the Einstein ring radius, the radius of the symmetric ring image of the source when lens and source are perfectly aligned.) From the probability distributions of the mass ratios and projected separations, we construct a data set from the detections and plot this data in the displayed figure to see how well it can be interpreted.

From the figure the mass ratios are seen to be reasonably good signatures of the actual masses of the planets because the lens masses span only an order of magnitude, whereas the planetary masses span three orders of magnitude. Lower mass planets tend to fall inside the Einstein ring radii R_E and higher mass planets outside thereby recovering this solar system characteristic in the assumptions. ($R_E \approx 4$ AU for a solar mass star at 4 kpc lensing a star in the galactic center at 8 kpc.) The concentration of Earths at $r/R_E \approx 1$ is the set of Earths at 2.5 AU. We could infer this distance from the fact that the highest probability of detection is for r near R_E, and R_E is near 2-3 AU for most of the likely lens masses. The striking concentration of higher mass planets near $r/R_E = 1.5$ reflects the fact that these planets have semimajor axes larger than R_E for nearly all lenses, but have the highest probability of being detected if their projected separations are close to R_E. The detection of 16 terrestrial mass planets implies that such planets are common given their low probability of detection. The finding of most planets with $m/M \sim 10^{-3}$ having $r/R_E > 1$ implies that most Jupiters are relatively far from their stars so processes that would move them much closer than their formation distances did not dominate planetary system histories. Finding the Jupiters far away from their stars would imply terrestrial planets closer to the stars even though the latter were not detected directly. Finding Uranuses where Jupiters should be would support the suspicion that Jupiters are hard to make. Most of the terrestrial mass planets in our sample are detected about M stars at such distances from their stars that water is likely to be frozen. However, the habitable zone would be expanded to greater distances for terrestrial planets exceeding an Earth mass, where a more massive atmosphere could enhance greenhouse warming above what we experience. Fewer terrestrial planets are detected in the other two models of the dependence of planet mass and planet-star distance on lens mass, but many Jupiters are always found if they are at distances close to where they could be formed. If the Jupiters are there, they will be detected beginning almost immediately after the start of the search.

Care must be taken in inferring the fraction of lenses having planets from the number of planets detected and the probabilities of detection, since the latter are dependent on the assumptions about planetary distributions and the lens mass function. The relative ease with which the more massive planets can be detected and the implications about the survivability of terrestrial planets if the former traverse the latter's domain may mean that the most important contribution of a microlensing search for planets may be to determine where the Jupiters are relative to their central stars rather than the direct detection of a few terrestrial planets.

References

Alcock, C. *et al*, 1997, *Astrophys J*, In Press
Beichman, C.A. (Ed) 1996 A Road Map for the Exploration of Neighboring Planetary Systems, JPL Pub 92-22, Pasadena, CA
Butler, R.P. and G.W. Marcy 1996, *Astrophys J.*, **464**, L153.
Butler, R.P. *et al*, 1997, *Astrophys. J.* In Press. Cochran, W.D. *et al*, 1997, *Astrophys. J.* Submitted. Gould, A. and A. Loeb, 1992 *Astrophys. J.*, **396**, 104.
Lin, D.N.C. *et al*, 1996, *Nature*, **380**, 606.
Mao, S. and B. Paczynski 1991, *Astrophys. J.* **449**, L37.
Marcy, G.W. and R.P. Butler 1996 *Astrophys. J.* **464**, L147.
Mayor, M. and D. Queloz, D. 1995, *Nature*, **378**, 355.
Peale, S.J. 1997, *Icarus*, (submitted).
Rasio, F.A. and E.B. Ford, 1996, *Science*, **274**, 954.
Tytler, D. 1995, http://techinfo.jpl.nasa.gov/WWW/ExNPS/RoadMap.html Also in *A Road Map for the Exploration of Neighboring Planetary Systems*, JPL Pub 92-22, Pasadena, CA, C.A. Beichman Ed., 1996 p 7-10.
Ward, W.R. 1996 *BAAS*, **28**, 1112.
Weidenschilling, S.W. and F. Marzari, 1997, *Nature* (submitted).